# Development & Implementation of Groundwater Monitoring Criteria Pursuant to SB4

***December 11, 2014***

terraphase engineering

# Presentation Outline

- Problem definition
- Overview of well stimulation treatment (WST) in California
- Review of existing regulation of WST in California
- Conceptual model for potential impacts of WST to groundwater
- Potential pathways to groundwater
- Key groundwater monitoring criteria
- Groundwater monitoring scales
- Examples of area-wide monitoring
- WST-related analytical parameters
- Summary

# Problem Definition

- **Overarching objective**
  - Protect California's groundwater supplies in the vicinity of WST areas
- **Approach**
  - Develop SB-4 groundwater monitoring criteria to ensure that WST fluids and related formation fluids do not impact local groundwater supplies
- **Existing groundwater protection**
  - Oil/gas production and produced water injection wells regulated in California by DOGGR through drilling/construction permits isolating freshwater zones
  - DOGGR also protects groundwater resources through regular casing integrity testing, idle well and well abandonment programs
- **SB-4 groundwater protection per pending DOGGR regulations**
  - Regulations to maintain WST fluids in target formation through detailed permitting with preconstruction analysis; pressure monitoring, testing & reporting before, during & after WST
- **Challenges**
  - Proving a negative
  - Small volume of WST fluids relative to formation water
  - Limited pathways – multiple procedures in place to eliminate potential pathways
  - ➢ *Potential for WST fluids reaching protected groundwater is a function of several factors, requiring a tiered approach to groundwater monitoring*

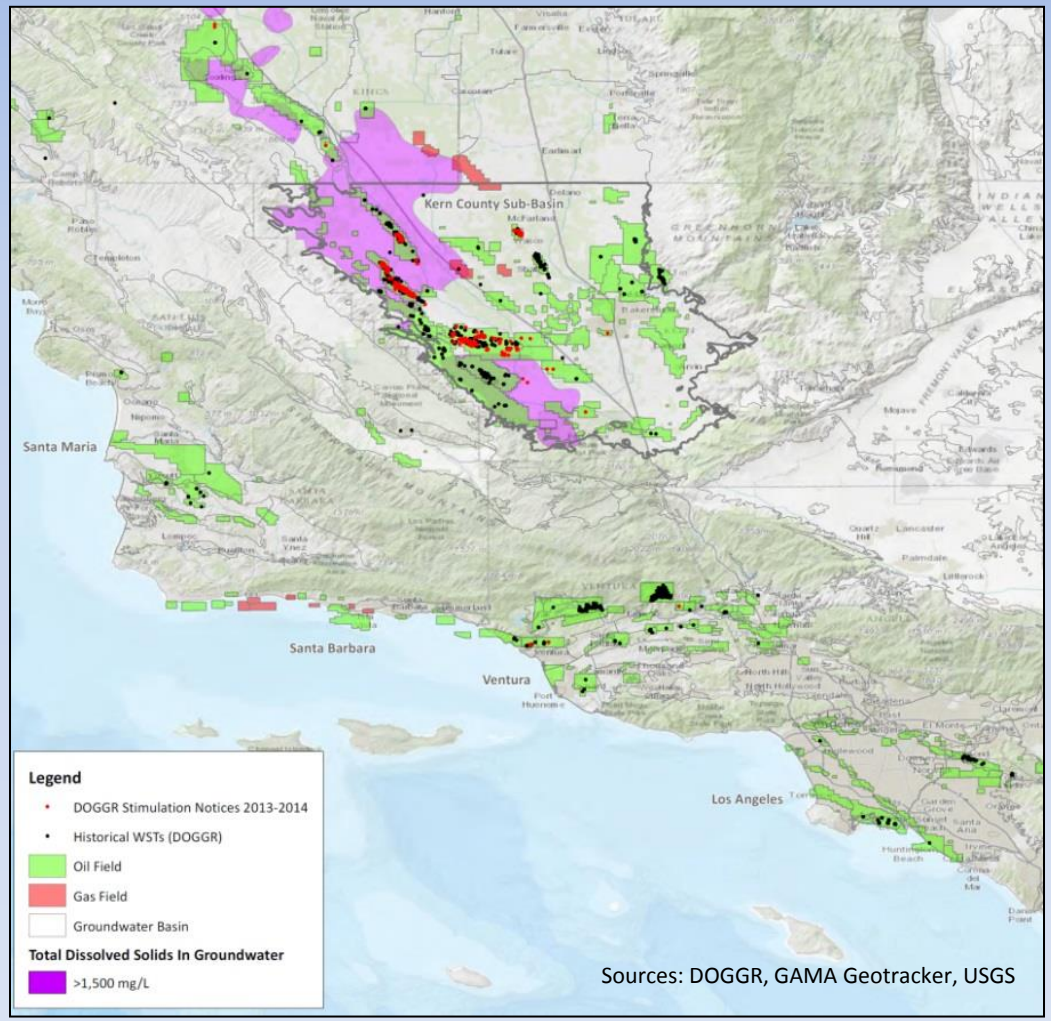
# Well Stimulation Treatment in California

# WST in California – Overview

- WST conducted in California since 1953, with no documented groundwater impacts (CCST 2014)
- As defined in SB4, WST includes:
  - Hydraulic fracturing treatment, and
  - Acid well stimulation
- Annual rate of WST is relatively low (about 1,200 events per year; CCST 2014) compared to other states, e.g., Texas, where more than 10,000 wells are hydraulically fractured each year
- Performed primarily in vertical wells, as compared with the extensive horizontal stimulation taking place in the East Coast and Midwest of the US
- Freshwater zones isolated from oil/gas horizons by DOGGR regulation of WST well drilling, construction and operation in California

# WST in California – Overview

- Large fraction of WST in California takes place in areas with naturally poor-quality groundwater

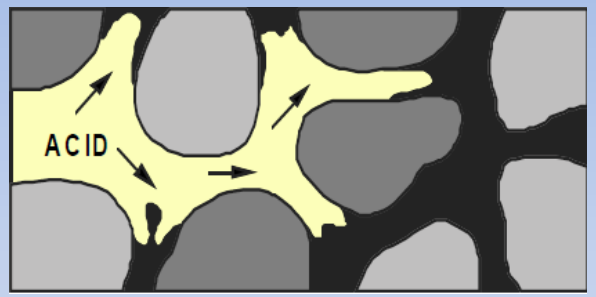



*Southern California Oil and Gas Fields, WST Wells, and Shallow Groundwater Quality in San Joaquin Valley*

# Hydraulic Fracturing in California

- Uses much smaller volumes of hydraulic fracturing fluid than in other states, with average volume of 130,000 gallons per event in CA (CCST 2014), compared with millions of gallons used on the East Coast per WST event
- WST in California occurs in younger, less brittle rocks than on East Coast with a lower potential for fracture propagation
- Hydraulic fractures in CA WST propagate 10s to 100s of feet
- Pressure in well and volume of fracturing fluids are monitored throughout process, with immediate response and management of anomalous conditions
- Pressure monitoring and fluid volumes and composition are recorded and reported to DOGGR and made available to public in database

# Acid Well Stimulation in California

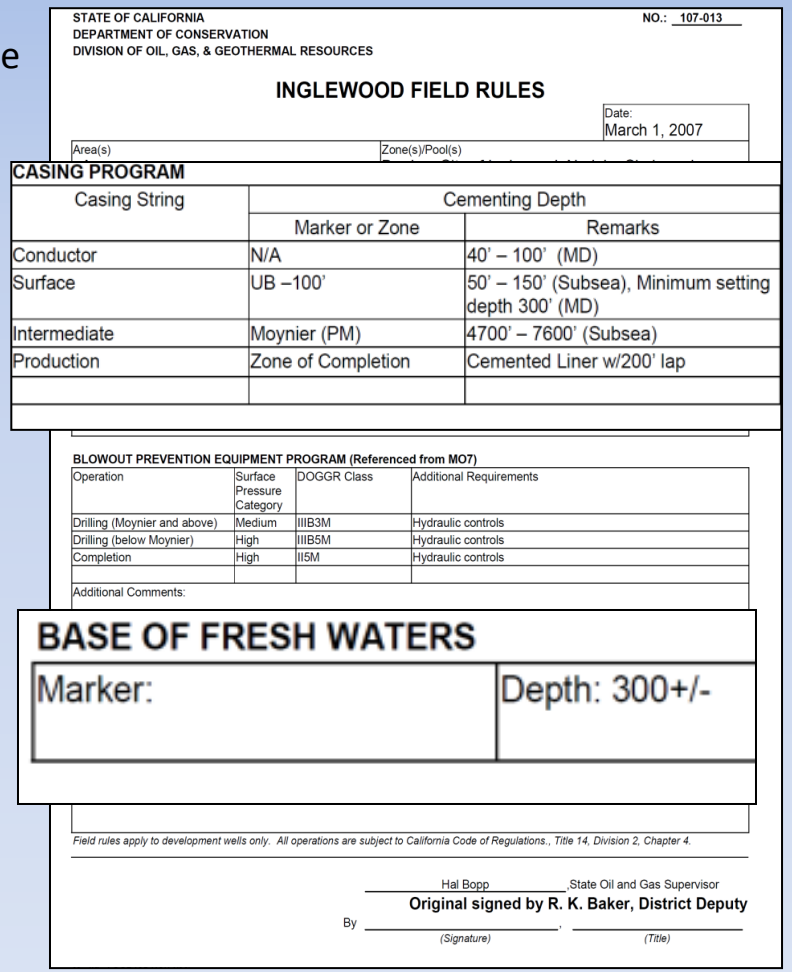



- Performed to address clogging in immediate area of the oil well created during drilling process (powdered rock fragments fill natural pore spaces)
- Clears the effective zone of clogging that may be a few inches from the wellbore to tens of feet, but is typically less than 10 feet from wellbore
- Restores natural reservoir rock permeability, does not increase original natural pore spaces
- Acid is introduced at pressures lower than fracture gradient, with no fracturing of reservoir or well seals
- Casing pressure monitored continuously during stimulation
- Acids are neutralized through interaction with natural minerals - not mobile

# Oil/Gas Field Regulations in California

# Existing Regulation of Well Construction & Abandonment

- **Oil well drilling and reworking**
  - Field rules for each area identify production zones, base of fresh water
    - Freshwater zones protected
  - Detailed hydrogeologic analysis with depth-specific casings, cementing type and volume and perforations
  - Drilling activities reported to and observed by DOGGR
  - Completion reporting with any deviations and integrity testing
- **Idle well program**
  - Surface pressure and annual fluid level monitoring
  - Casing integrity bi-annual testing
  - Required action for failure
- **Well abandonment**
  - Detailed well abandonment permits
  - Protection of fresh water zones and surface water
  - Isolation of hydrocarbon zones
  - Abandonment reporting with depths cement testing
  - Abandonment activities reported & observed by DOGGR



STATE OF CALIFORNIA
DEPARTMENT OF CONSERVATION
DIVISION OF OIL, GAS, & GEOTHERMAL RESOURCES

NO.: 107-013

**INGLEWOOD FIELD RULES**

Date: March 1, 2007

Area(s) | Zone(s)/Pool(s)

**CASING PROGRAM**

| Casing String | Cementing Depth | |
|---|---|---|
| | Marker or Zone | Remarks |
| Conductor | N/A | 40' – 100' (MD) |
| Surface | UB –100' | 50' – 150' (Subsea), Minimum setting depth 300' (MD) |
| Intermediate | Moynier (PM) | 4700' – 7600' (Subsea) |
| Production | Zone of Completion | Cemented Liner w/200' lap |
| | | |

**BLOWOUT PREVENTION EQUIPMENT PROGRAM (Referenced from MO7)**

| Operation | Surface Pressure Category | DOGGR Class | Additional Requirements |
|---|---|---|---|
| Drilling (Moynier and above) | Medium | IIIB3M | Hydraulic controls |
| Drilling (below Moynier) | High | IIIB5M | Hydraulic controls |
| Completion | High | II5M | Hydraulic controls |
| | | | |

Additional Comments:

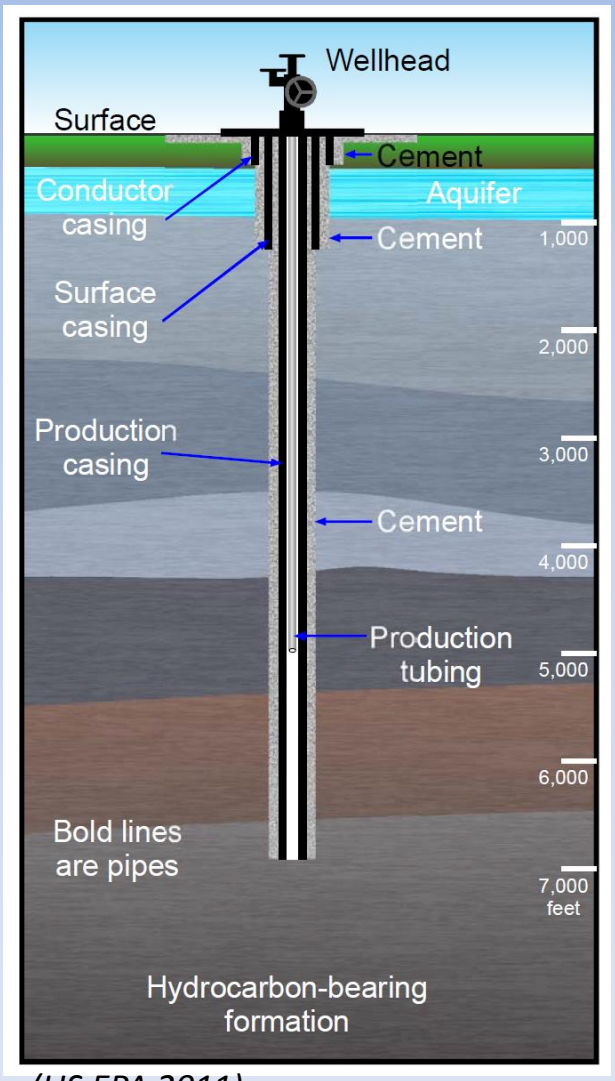
**BASE OF FRESH WATERS**

| Marker: | Depth: 300+/- |
|---|---|

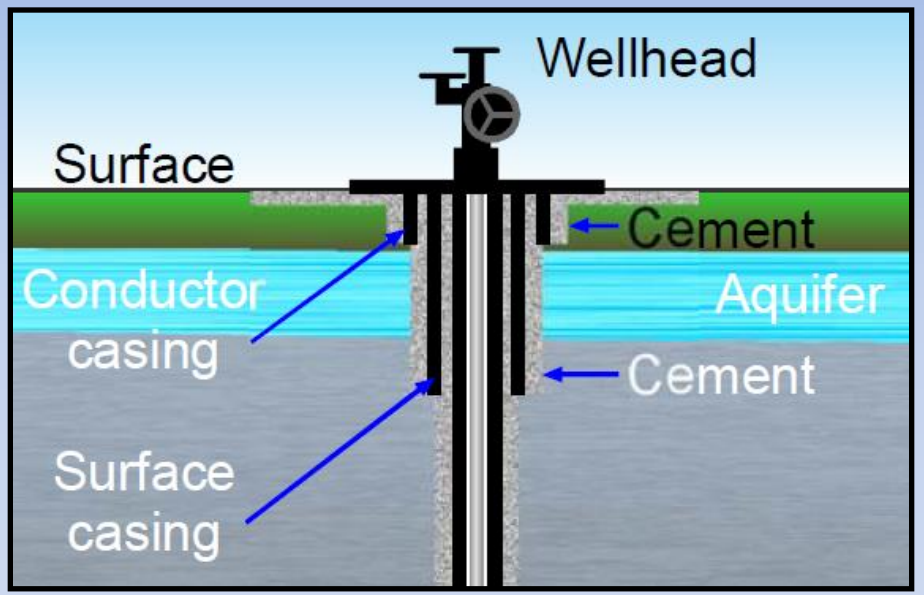
*Field rules apply to development wells only. All operations are subject to California Code of Regulations., Title 14, Division 2, Chapter 4.*

Hal Bopp, State Oil and Gas Supervisor
**Original signed by R. K. Baker, District Deputy**
By _____ (Signature) _____ (Title)

# Typical Oil Production Well/WST Well Design




*(US EPA 2011)*




**Groundwater protection features include:**

- Multiple cemented casings
- Surface casing must extend below protected groundwater
- Cementing must be witnessed by DOGGR engineer
- Post-cement pressure test
- Driller's log

# Additional DOGGR Regulations of WST Wells, per SB4

- **Detailed WST Well Design and Fracturing Description for DOGGR Approval**
  - WST well construction details (casing, cement, integrity and pressure testing)
  - Depth and location of WST stages
  - Complete listing of WST chemicals and source water
- **Required Permitting Analysis of Hydrogeologic Features Surrounding WSTs**
  - Freshwater zones, barriers, faults, characteristics of hydrocarbon production zones
- **Required Permitting Analysis of Potential Conduits Surrounding WSTs**
  - Active, idle or abandoned oil/gas, produced water injection and WST wells
  - Water supply wells
- **WST Fluid Handling**
  - SPCC, Emergency Response Plan, agency notifications and compliance
- **Report of WST Activities within 60 Days of Completion**
  - Composition of WST flow back water (collected after between 1 and 3 well volumes) for lab analysis
  - The pressures recorded during the well stimulation treatment and during first 30 days
  - Description of any difference between the actual well stimulation treatment and the well stimulation treatment design and permit application

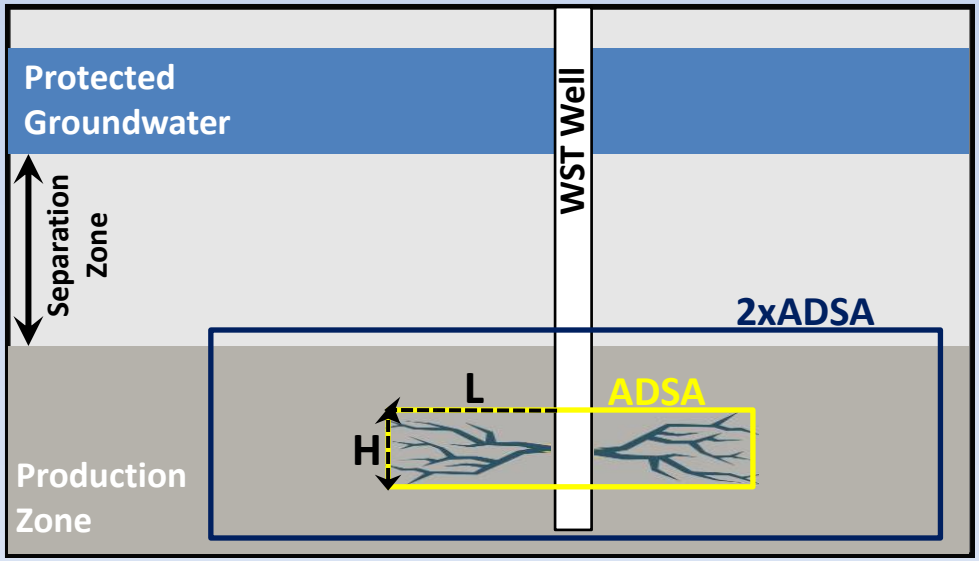
# SB-4 DOGGR Regulations WST "Safety Factor" (2xADSA)

DOGGR SB-4 Regulations define the **"axial dimensional stimulation area" (ADSA)** for each WST stage as follows:

- estimated length (L; measured perpendicular to the wellbore)
- estimated height (H; measured perpendicular to the length), and
- direction of the induced fractures or other planned modification

DOGGR regulations require identification of:

- existing wells, including plugged and abandoned wells, that may be impacted by WST fractures and modifications in the same production horizon **within the area of twice the ADSA (2x ADSA)**
- Geologic features, such as faults, **within 5xADSA**



# Conceptual Model

# Conceptual Model – Risk Evaluation

- Risk evaluation components

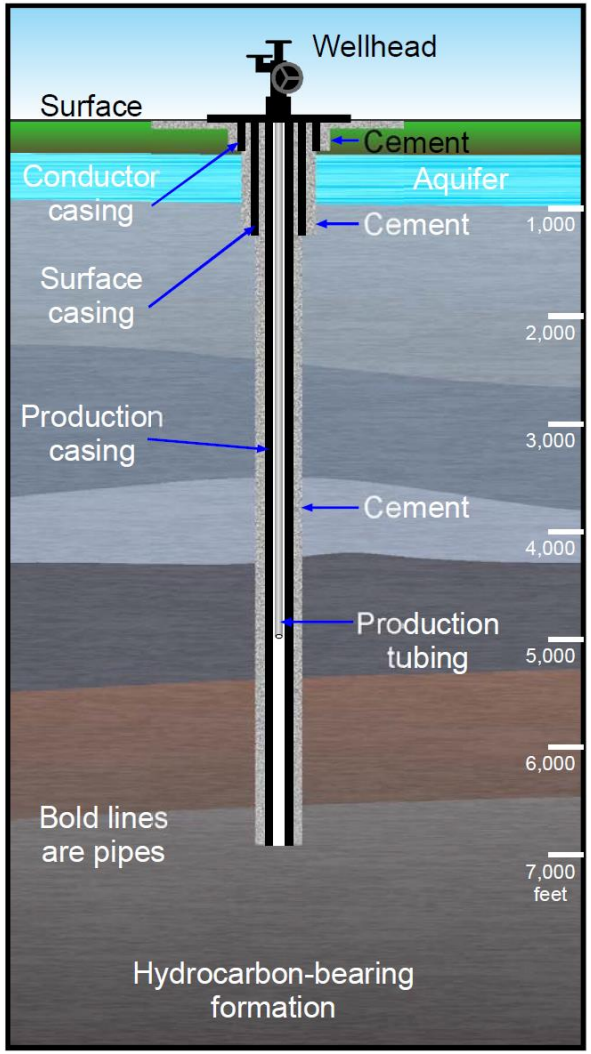
  *Source → Pathway → Receptor*

- Potential Sources
  - WST fluid/formation fluid release in frac zone
  - WST fluid/flowback fluid release due to casing failure
- Potential Pathways
  - WST casing failure
  - Matrix flow
  - Fracture flow
  - Vertical conduits
    - Active or idle wells
    - Abandoned wells
    - Faults
- Groundwater Receptor

# Potential Pathways

# Leaking WST Well Casing

- WST well has tubing, casing and cement, which all protect surrounding aquifers and formations
- Pressure and integrity monitoring performed before, during and after WST
- Detailed monitoring takes place throughout WST event – no long-term undetected releases possible
- Leakage in casing will be detected in real time during WST by pressure changes and rate of WST fluid flow
  - ➢ *WST then stopped and breaches mitigated immediately*
- WST construction is most protective in fresh-water zones
- **Potential of leakage from WST wells reduced to near zero through many layers of casing/cement, real-time integrity and pressure testing, which is monitored in the field and reported to DOGGR**



# Matrix Flow of WST Fluids to Groundwater

- WST performed in tight rock formations; permeability (*k*) in target zones in California typically around or below 1 millidarcy (mD; CCST 2014)
- Vertical permeability in horizontally stratified sedimentary basins is substantially lower than horizontal permeability due to anisotropy (Freeze and Cherry 1979).
- Formations overlying the hydrocarbon zone include “cap rock” or “seals” of similarly low *k*.
- Consequently, vertical fluid travel times in sedimentary basins are often on the scale of millions of years (Flewelling and Sharma 2014)
- Vertical stratification of hydrocarbon zones and fresh groundwater is proof that matrix flow of fluids from hydrocarbon zones to fresh groundwater does not occur
- No demonstrated cases of WST fluid matrix flow to overlying fresh groundwater

➢ **Hydrogeologic conditions and mandated procedures eliminate matrix flow as a viable potential pathway**

# Fracture Propagation to Groundwater

- Factors that limit fracture propagation include:
  - **WST fluid volume** (Flewelling et al. 2013)
    Fractures generated by WST in California are much shorter than those generated in most parts of the US, because of a much smaller volume of water injected over a shorter injection time. Typical fracture lengths in California are 150 to 300 feet (DOGGR 2014).
  - **Frac barrier formation** (King 2012)
    If pressure is maintained, fractures will extend vertically until they reach more ductile (softer) rock, which is more difficult to fracture than brittle rock (Wang and Gale 2009), and will cause the energy to dissipate.
  - **Leakoff** (Engelder 2012)
    Fluids moving through the fractures will "leak off" into the formation matrix through imbibition, through the large surface area created by the WST event in the frac zone.

# Fracture Propagation to Groundwater, cont.

- Fractures generated by WST propagate over distances in the range of 100 to 1,000 feet (Keck and Withers 1994; Fisher and Warpinski 2011, 2012; CCST 2014), with typical fracture lengths in California of 150 to 300 feet
- WST is a highly controlled, carefully planned, and regulated process in California; microseismic data have confirmed the ability to predict fracture propagation (Warpinski 2013)
- WST events are short (hours), after which formation pressure quickly decreases (Kissinger et al. 2013); subsequent hydrocarbon extraction creates a low-pressure zone
  - *Therefore, the high upward pressure gradient required for fluids to migrate vertically is absent (Flewelling & Sharma 2014)*
- Consequently, fractures created during WST will remain within a small, predictable, and measurable volume surrounding the WST
- No demonstrated cases in the literature of WST fracture propagation to fresh groundwater

➢ **Fracture propagation to groundwater is highly unlikely and infeasible when sufficient separation exists between frac zone and groundwater**

# Potential Vertical Conduits: Faults

- Flow of frac/formation fluids along faults to overlying groundwater requires a fault to be substantially more permeable than the rock matrix, and continuously open throughout its vertical length; however, faults are rarely "open" planes
- Vertical stratification of hydrocarbon zones and fresh groundwater, resulting from processes that occur on geological time scale, indicate fluid flow along faults from hydrocarbon zones to fresh groundwater generally does not occur (natural oil seeps are an exception)
- Absence of brine/oil in groundwater overlying oil production zones indicates oilfield activities have not "opened up" existing faults nor created new permeable faults (Fisher and Warpinski 2011).
- Presence of trapped buoyant oil and gas, and the occurrence of continuous, permeable faults are mutually exclusive (Flewelling et al. 2013)
- Numerical simulations (Rutqvist et al. 2013) & analytical solutions (Flewelling et al. 2013) indicate energy released during a WST event can result in maximum fault rupture lengths of 30 to 60 feet
- No demonstrated cases of WST fluids moving through faults to overlying fresh groundwater
- Probability of frac fluid transport to groundwater along faults is remote; faults are addressed by DOGGR in WST permitting requirements under SB-4

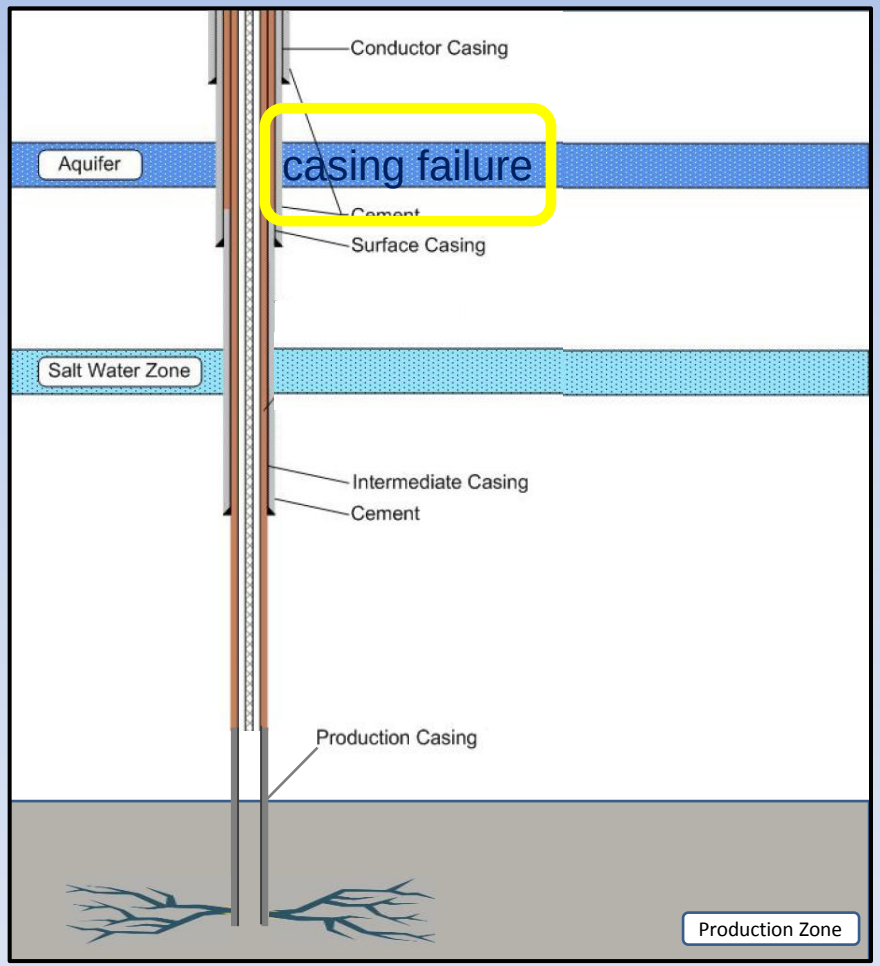
➢ **Faults are highly unlikely to act as vertical conduits to groundwater**

# Potential Vertical Conduits: Idle and Abandoned Wells

- Idle and abandoned wells are potential conduits for flow of WST fluids to protected groundwater, if the pathway is complete, i.e.,
  - *The well has to be within the potential spatial influence of the WST event (defined as 2xADSA)*
  - *The well must be in both the oil and protected groundwater zones*
  - *An idle oil well or improperly abandoned well must have a casing failure within the protected groundwater zone*
  - *There must be sufficient upward pressure to drive WST fluids towards and into the protected groundwater zone*
- Pending DOGGR regulations account for presence and potential influence of wells as vertical conduits during WST
  - *DOGGR regulations and new regulations based on SB 4 require identification and consideration of wells within the 2xADSA distance when planning and permitting a WST event*

➢ **Likelihood of idle and abandoned wells to act as vertical conduits is limited by several conditions required for a complete pathway.**

# Potential Sources and Pathways Related to WST

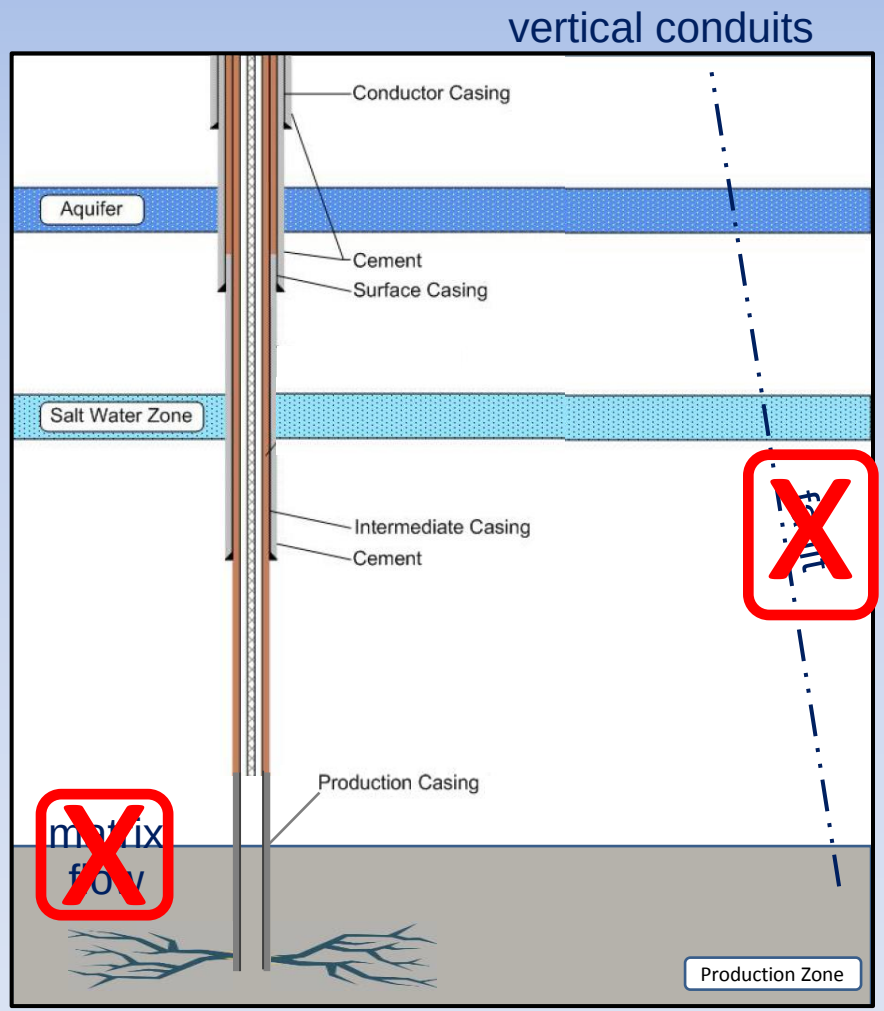



*Modified from: US DOE, Modern Shale Gas Development in the United States.*

- Real-time monitoring before during and after WST
- Detectable event - monitoring would detect potential release

➢ ***Groundwater monitoring only required if release occurs into protected water zone***

# Potential Sources and Pathways Related to WST




not viable pathways

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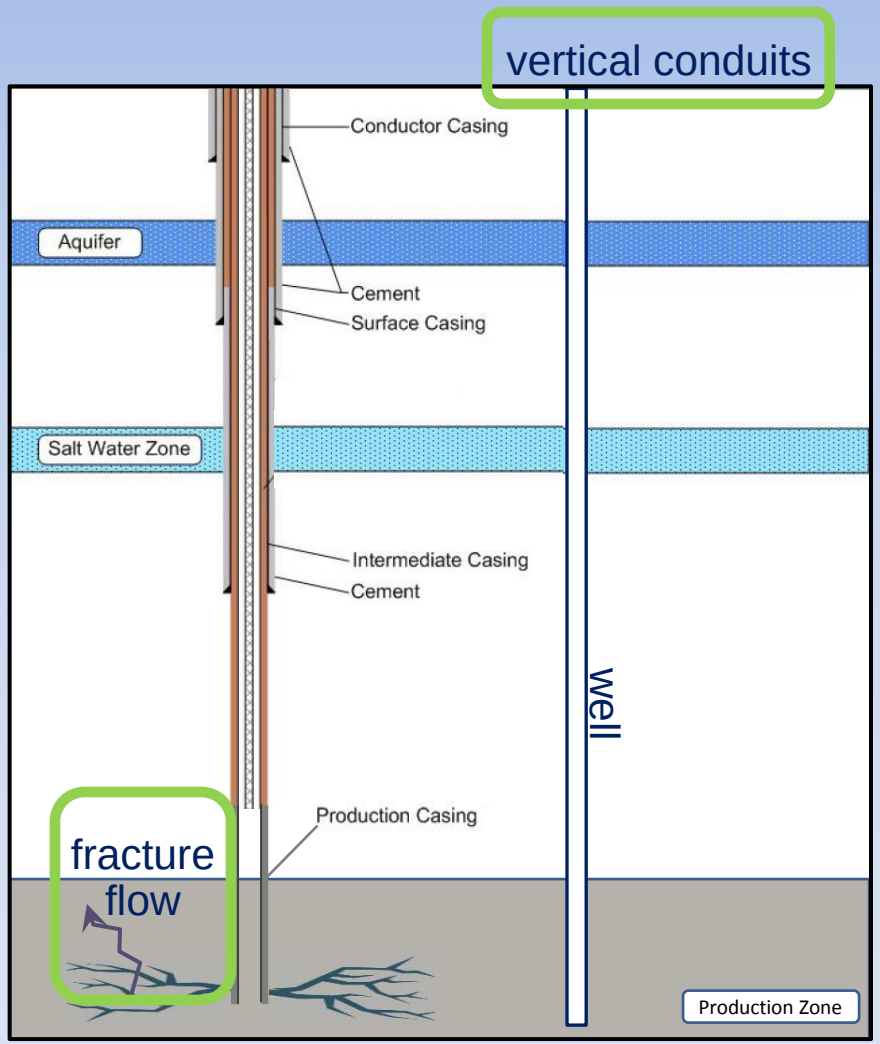
# Potential Sources and Pathways Related to WST




*Modified from: US DOE, Modern Shale Gas Development in the United States.*

- Potential pathways
  - Vertical conduits
  - Fracture flow
- Viable under certain conditions

➢ ***Monitoring should be evaluated if potential for complete pathway exists – i.e., if < 2xADSA***

# Groundwater Monitoring Criteria

# Key Groundwater Monitoring Criteria

- Groundwater quality
- Presence of potentially complete pathways

# Key Groundwater Monitoring Criteria

- Groundwater quality considerations
  - Groundwater exceeding Underground Sources of Drinking Water (USDW) exemption criteria
    - TDS > 10,000 mg/L
  - Groundwater exceeds Basin Plan criteria but meets USDW exemption criteria
    - 3,000 < TDS < 10,000 mg/L
  - Groundwater meets Basin Plan criteria
    - TDS < 3,000 mg/L
  - Hydrocarbon production zone
  - Not reasonably expected to serve a public water system
  - Previously exempted groundwater

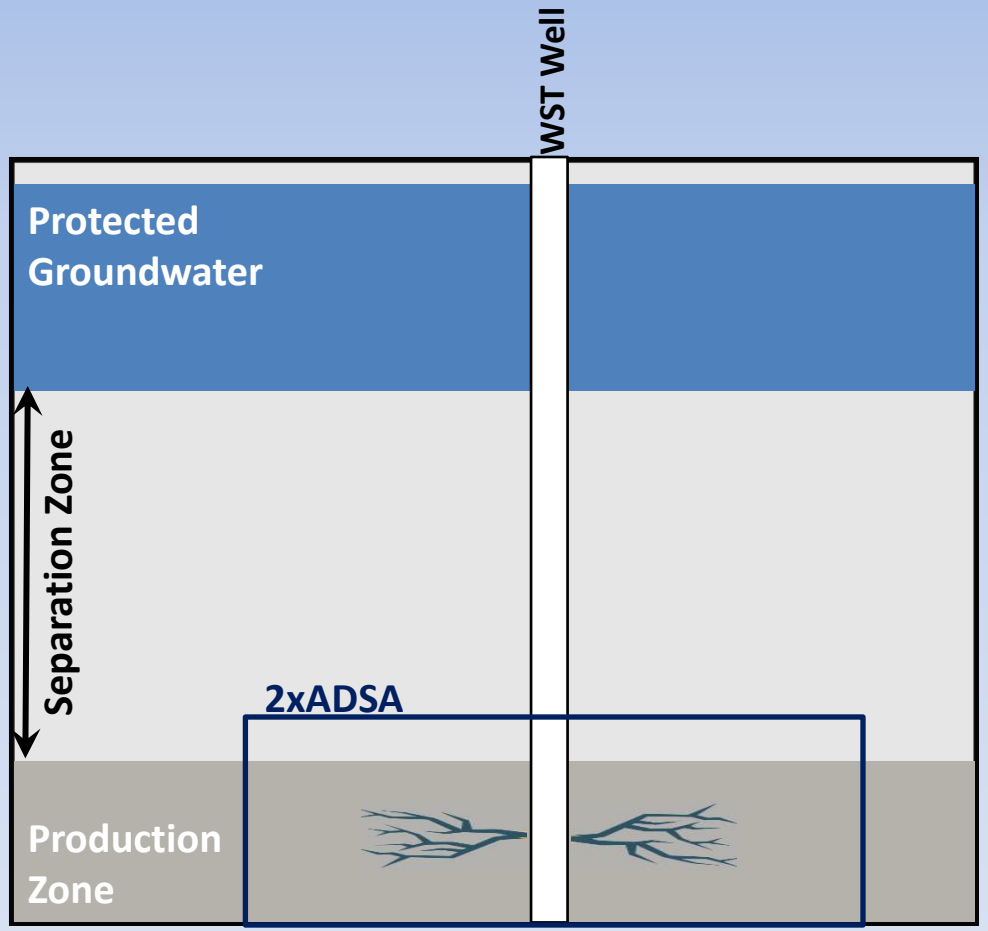
➢ ***Monitoring effort should be commensurate with groundwater quality***

# Key Groundwater Monitoring Criteria

- Are there potentially complete pathways?
  - Potential vertical conduits within 2 times the “axial dimensional stimulation area” (2xADSA)?
  - Separation between WST depth and protected groundwater < 2xADSA?

➢ ***Monitoring should only be considered if there are potentially complete pathways***

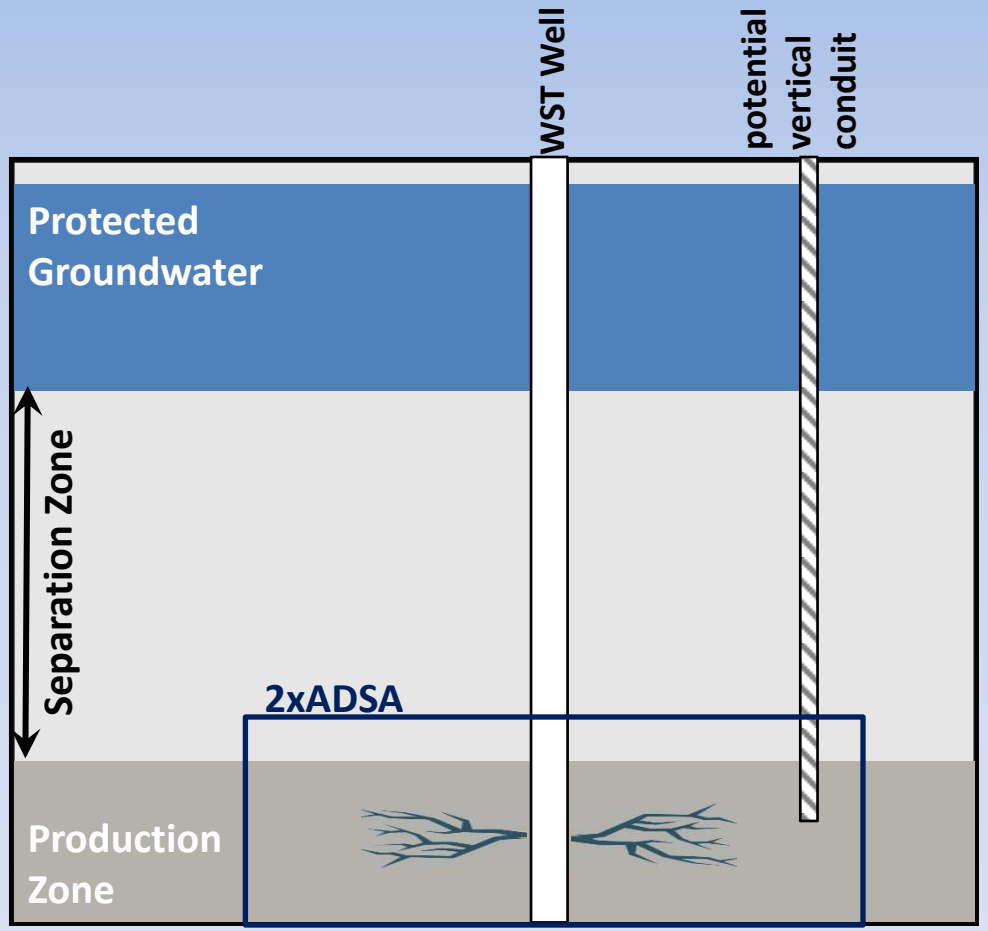
# Groundwater Monitoring Criteria – Scenario 1




| Screening Criterion | Present? |
|---|---|
| Protected Groundwater? | YES |
| Vertical Conduits <2xADSA? | NO |
| Separation <2xADSA? | NO |

- No potential pathways
- No monitoring

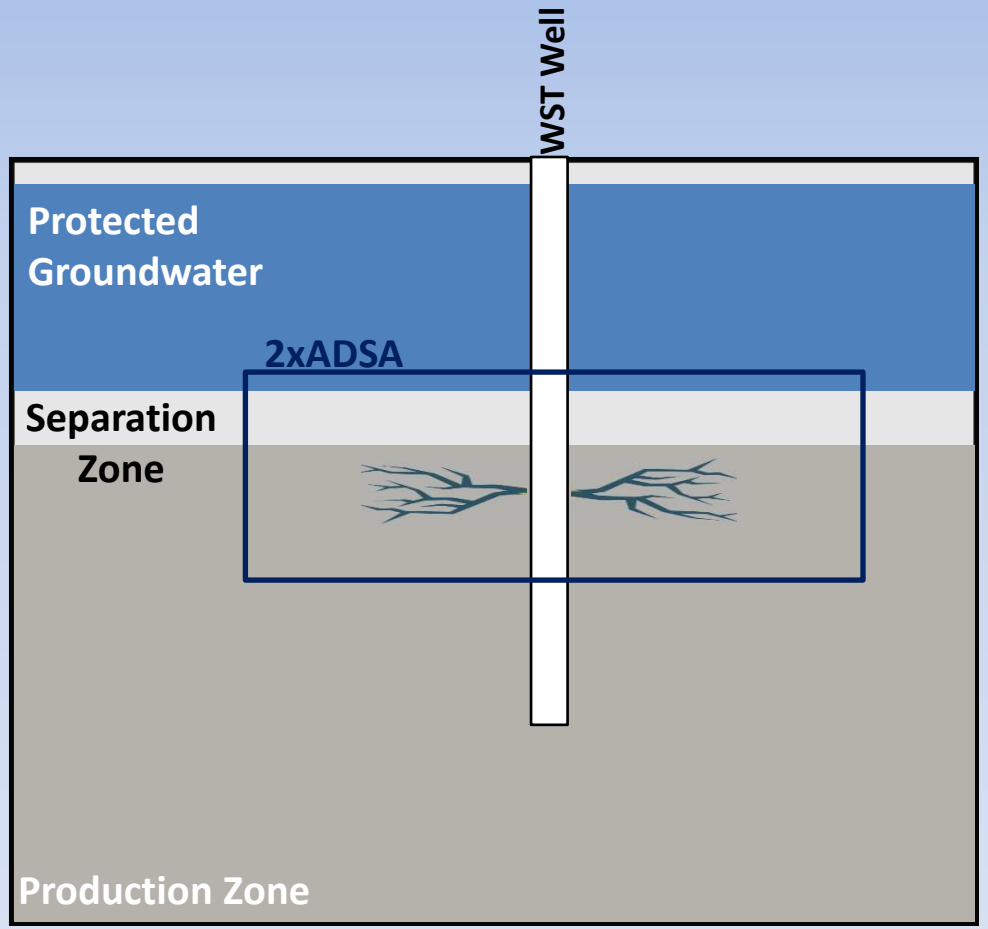
# Groundwater Monitoring Criteria – Scenario 2




| Screening Criterion | Present? |
|---|---|
| Protected Groundwater? | YES |
| Vertical Conduits <2xADSA? | YES |
| Separation <2xADSA? | NO |

- Viable potential pathway exists
- Monitoring should be considered, commensurate with groundwater quality

# Groundwater Monitoring Criteria – Scenario 3




| Screening Criterion | Present? |
|---|---|
| Protected Groundwater? | YES |
| Vertical Conduits <2xADSA? | NO |
| Separation <2xADSA? | YES |

- Viable potential pathway exists
- Monitoring should be considered, commensurate with groundwater quality

# Groundwater Monitoring Scales

# Groundwater Monitoring Scales

- **Area-wide monitoring**
  - "Area" can be defined as an oilfield or a portion of an oilfield
- **Single-project monitoring**
  - Can be "well-by-well" if only one WST; typically more than one WST event is planned and permitted at a time
- **Regional monitoring**
  - "Regional" scale remains to be defined; groundwater sub-basin seems appropriate

# Area-Wide Groundwater Monitoring

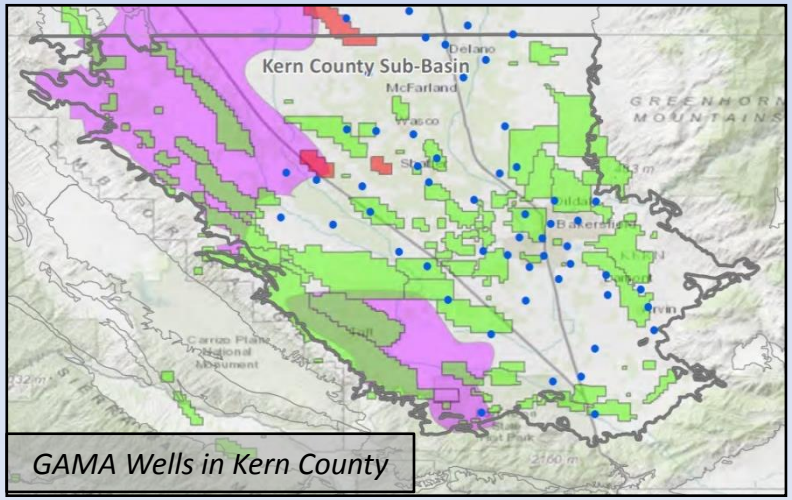
- Area can be defined as an oilfield or a portion of an oilfield
- Monitoring of potential impacts from a number of upgradient WST events within a defined area
- Network of strategically located monitoring wells
- More likely to detect groundwater impacts, should they occur, than monitoring on a single-project basis because of lateral dispersion as groundwater moves downgradient toward monitoring network
- Provides a “sentry” approach to evaluate if impacted groundwater is leaving the area
- Can be effective for WST events into the future, providing a robust, long-term data set suitable for statistical evaluation, that is more representative than a well-by-well approach

# Single-Project Groundwater Monitoring

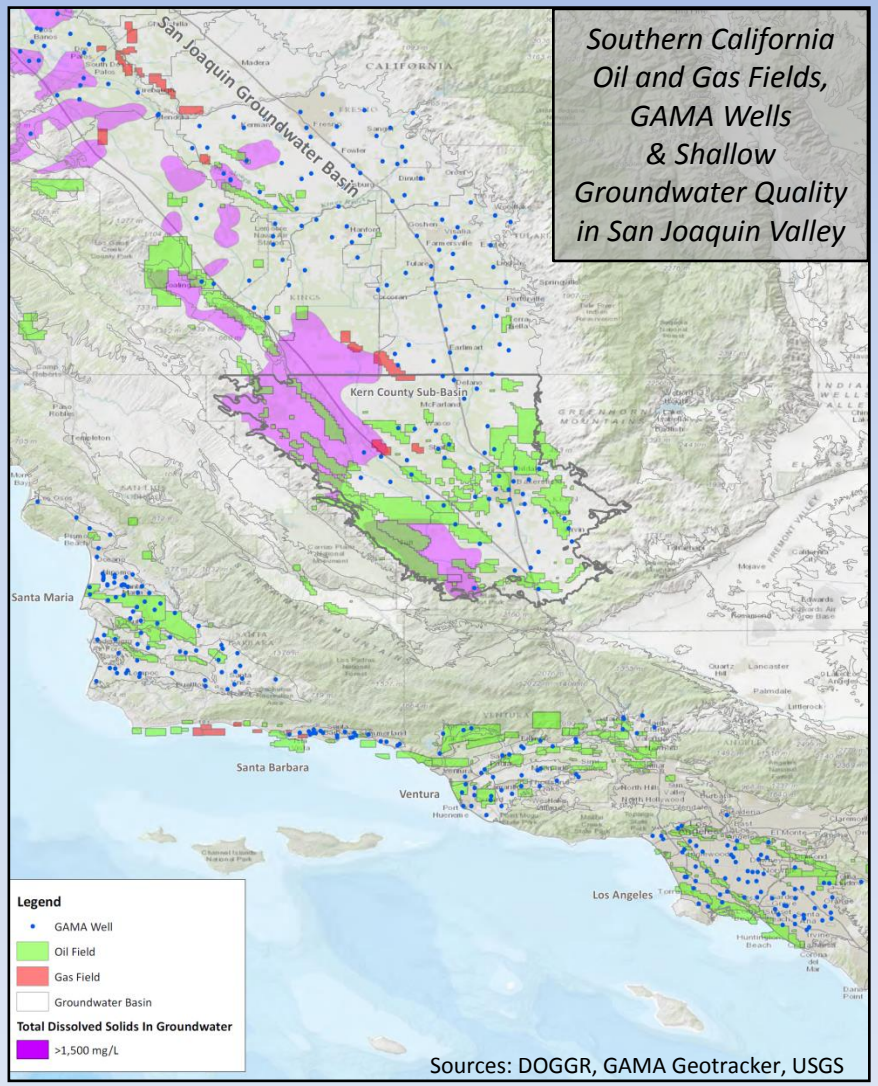
- Monitors potential impacts from one or a small number of WST events on a single-project basis
- Can be well-by-well if only one WST event is planned but typically multiple events are planned for each WST project
- Limited number of monitoring wells
- Although it may provide early detection, it is less likely to detect groundwater impacts than monitoring on an area-wide basis because of challenges of detecting a release close to source given the nature of potential pathways (primarily vertical conduits)
- If placed close to given WST event, monitoring well may not be useful for subsequent WST events
- Provides limited baseline and statistical data to evaluate post-WST results

# Regional Groundwater Monitoring

- Monitoring on groundwater sub-basin seems appropriate
- Existing GAMA well network
  - Extensive spatial coverage
  - Many well screens in zones of water supply
  - Historical data provide representative baseline conditions




*GAMA Wells in Kern County*

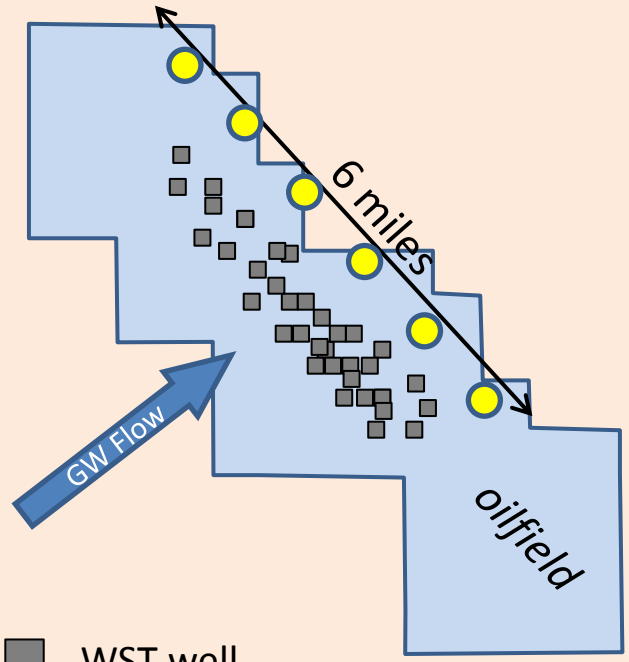



*Southern California Oil and Gas Fields, GAMA Wells & Shallow Groundwater Quality in San Joaquin Valley*

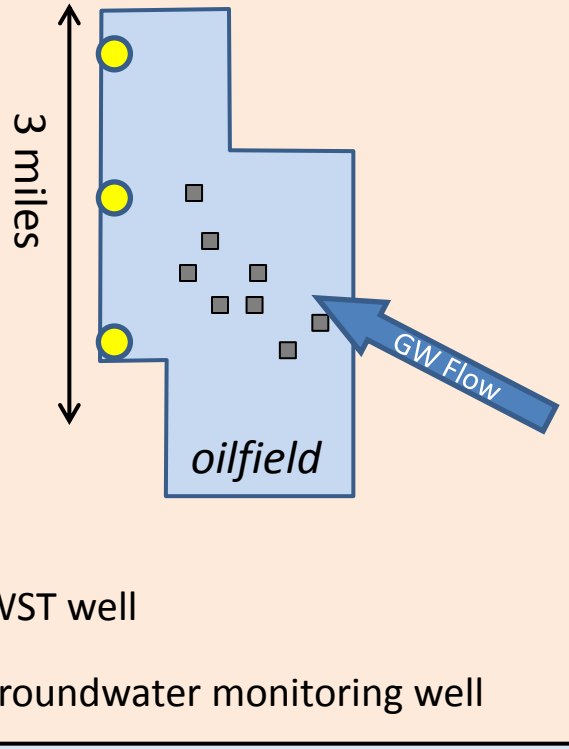
# Area-Wide Monitoring

# Examples of Area-Wide Monitoring

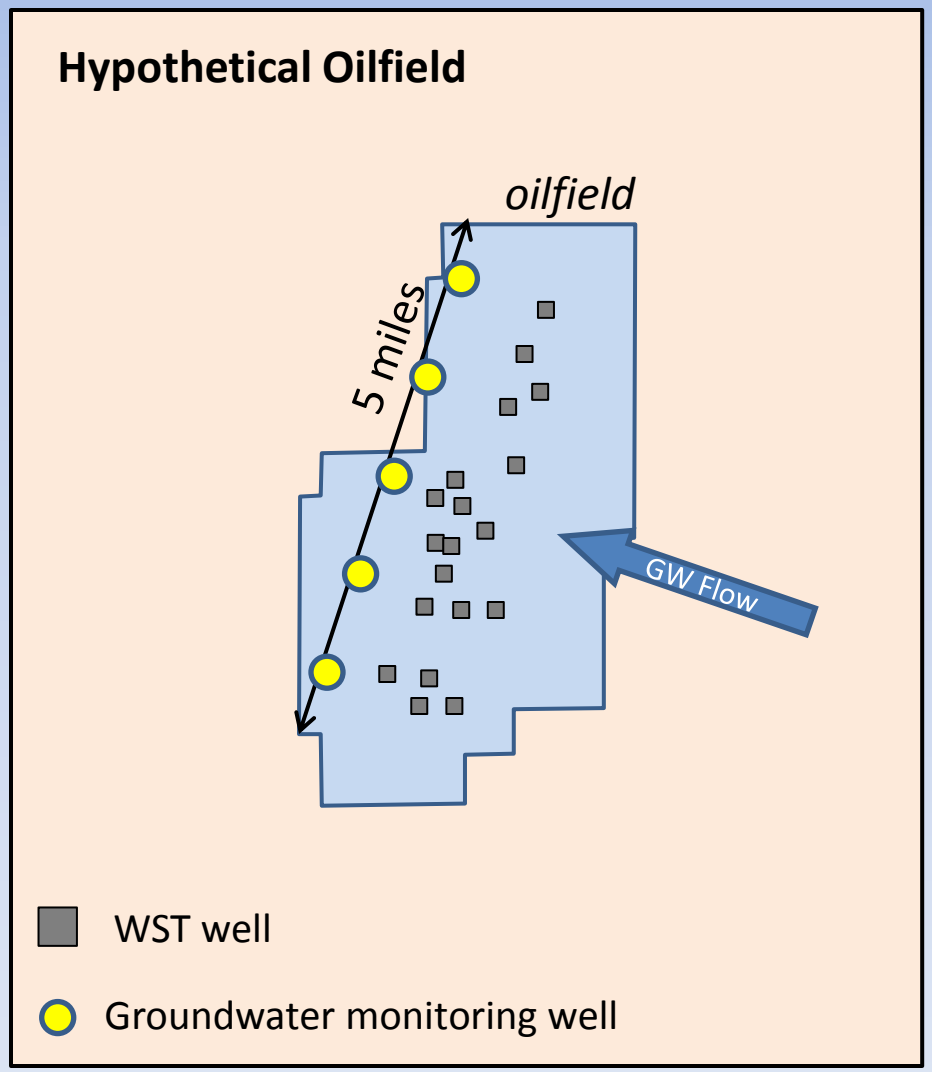
**Hypothetical Oilfield with High Density of WST Wells**




**Hypothetical Oilfield with Low Density of WST Wells**

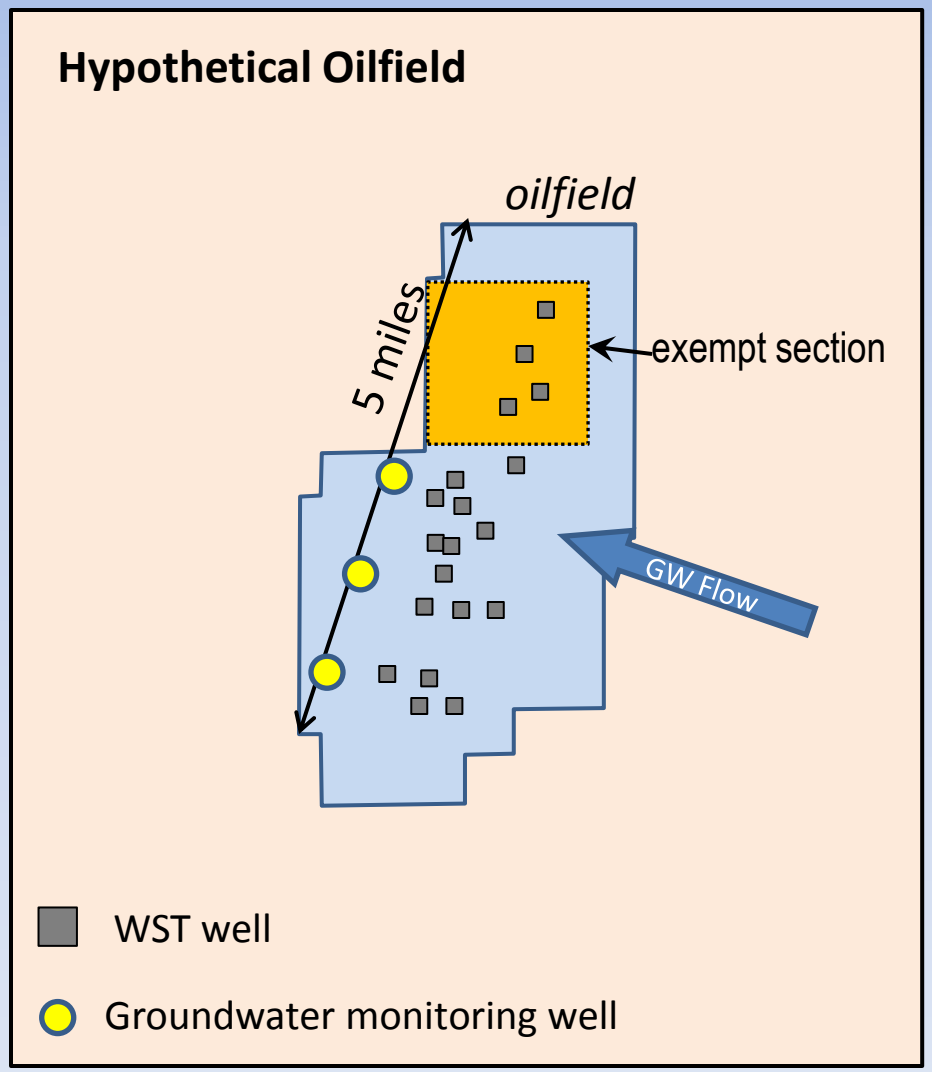


# Building an Area-Wide Monitoring Network




- The monitoring network is built iteratively
- Monitoring wells are installed as WST projects are developed
- Network of strategically located monitoring wells
- Once monitoring network in place, additional WST projects use existing wells for monitoring

# Building an Area-Wide Monitoring Network – Exempt Areas




- In oilfields with exempt sections, area-wide monitoring well network would be modified

# Monitoring Parameters

# WST-Related Analytical Parameters

| Parameter | Rationale |
|---|---|
| pH | Geochemical master variable; reflects general changes in water composition |
| TDS | Primary drinking water quality parameter. Indicator of potential arrival of high-TDS WST or formation fluids. Stable and not significantly affected by biological, physical or chemical degradation/attenuation. |
| Specific conductance | A proxy for TDS. Easily measured in the field. Could serve as field screening during post-WST events for the need for analysis of additional parameters. |
| total petroleum hydrocarbons (TPH) | Primary indicator of crude oil. May be naturally present in certain groundwater due to seeps or co-occurrence of oil and groundwater or may indicate the presence of non-WST impacts. |
| BTEX | Components of TPH with established regulatory drinking water standards. Low detection limits allow for early indication of TPH presence and may indicate the presence of non-WST impacts. |
| CAM-17 metals plus boron, iron, manganese (filtered) | Concentrations of certain metals elevated in produced water and brine. Certain metals are indicators of changing redox conditions. Care should be taken to account for natural geochemical cycles that can affect concentrations of redox-sensitive metals. Elevated background metals present in many areas of California (arsenic, cadmium for example) and should be documented in pre-WST sampling. |
| Major anions/cations, incl. bromide, iodide | Flowback and produced water tend to contain higher concentrations of sodium, chloride, and iodide than fresh water. Anion/cation ratios useful to evaluate potential changes in groundwater composition, and help distinguish natural (e.g. seasonal) fluctuations in groundwater composition. |
| Strontium | Higher concentration in flowback and produced water than in fresh water. |
| Dissolved methane (gas fields only) | Cautiously recommended indicator of formation gas, due to common presence and seasonal fluctuation in fresh water aquifers. May require multiple baseline measurements over time. Requires distinction between biogenic and thermogenic methane. |

# Summary

- No documented groundwater impacts from WST in CA to date
- SB-4 groundwater protection per pending DOGGR regulations will protect groundwater through rigorous permitting, testing and reporting
- DOGGR is notified of any WST well integrity issue at the time of occurrence; WST must cease immediately, with repairs conducted in real time
- Water Board notified in the unlikely event of WST fluid breach into protected groundwater; has been notified by DOGGR of releases to groundwater from oil/gas/produced water wells for > 30 years
- Monitoring should be considered only when potential pathways present within the 2xADSA distance
  - *Impacts to groundwater not possible without complete pathways*
- Monitoring effort should be commensurate with groundwater quality
- Area-wide groundwater monitoring is preferred over project-specific monitoring
- Operator should be able to choose between area-wide and project-specific monitoring based on site-specific conditions
- Regional groundwater monitoring should take advantage of GAMA well network on a groundwater sub-basin scale
- Groundwater analytical suites should focus on the most reliable indicators of formation fluids

# Questions?